Hydrogen-Based Energy Adoption in Aviation

How aerospace is progressing towards fully electrified aircraft

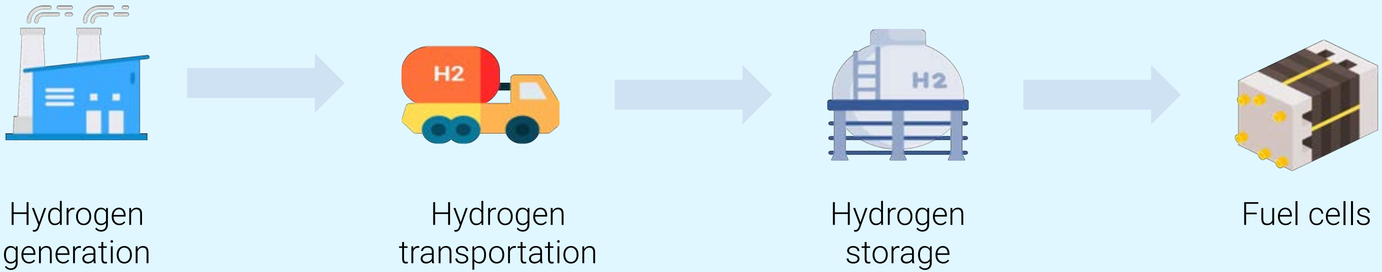
PRESCOUTER

Hydrogen-fueled aircraft have the potential to reduce the climate impact of flight by 50%-75%. In comparison to synthetic fuels, hydrogen combustion is 2-3x more effective in lowering emissions.

Hydrogen-based energy is the generation of energy that uses hydrogen and hydrogen-rich fuels in fuel cells. This type of energy can be integrated into renewable energy systems and has the potential to reduce the climate impact of the aviation sector. Aircrafts can be powered by hydrogen combustion through modified gas turbine engines, and combustion is achieved by using liquid hydrogen as fuel in the presence of oxygen. In power-hybrid systems, the addition of hydrogen fuel cells produces electrical power.

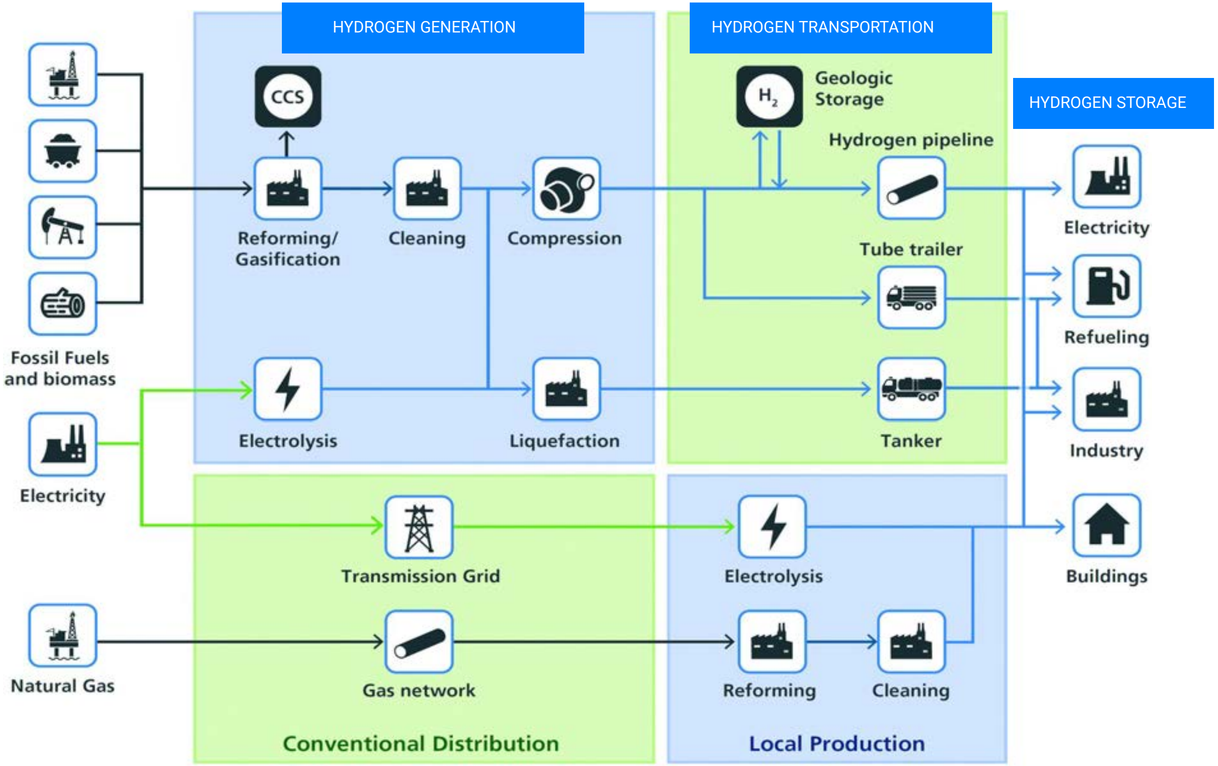
This report explains how hydrogen-based energy can be used in the aerospace and defense sector. We provide an overview of the different components required for hydrogen energy adoption in aviation, with a high-level description of each component and an example of the state of the art in each category. This report also illustrates a timeline for hydrogen fuel adoption, profiling recent developments from key players.

The Hydrogen Energy Value Chain



THE HYDROGEN ENERGY VALUE CHAIN

This graphic illustrates the wide variety of stakeholders that need to work together in order to make hydrogen a viable concept for the aerospace industry. From generation to transport and storage, the complexity of the ecosystem itself is one of the key roadblocks to success for this sector.



Source: Staffell et al., 2018.

Air Liquide - Generates hydrogen using steam methane reforming

TECHNICAL DESCRIPTION

Air Liquide uses Steam Methane Reforming to generate H_2 using desulfurized hydrocarbon as feedstock (natural gas, refinery offgas, liquefied petroleum gas, or naphtha). The feedstock is preheated, mixed with steam, and pre-reformed before passing a catalyst in a proprietary top-fired steam reformer to produce H_2, CO, and CO_2. The CO is shifted with steam to additional H_2 and CO_2. The H_2 is then separated using Pressure Swing Adsorption.

At a glance

Type	Hydrogen generation
Year	1902
Key Feature	Production of ultra-high purity, low-carbon hydrogen

SOLUTION HIGHLIGHTS

- Plant Capacity: 10,000 - 200,000 Nm^3/h of H2 (10,000 to 40,000 Nm^3/h for small-scale standard plants)
- Feed+fuel-steam: 12.3 to 13.2 MJ/Nm^3
- Steam production: 0.4 to 1.2 kg/Nm^3 of Hydrogen

Air Liquide's Steam Methane Reforming Plant with Pressure Swing Adsorption that recovers and purifies H2. H2 purity is 99.9%; the recovery rate fluctuates between 60%-90%, with a turndown as low as 25%. Source: Air Liquide.

Cummins: Manufactures alkaline electrolyzers and proton exchange membrane technologies

TECHNICAL DESCRIPTION

Cummins offers two series of electrolyzers: HySTAT (AEL) with a capacity range from 4 to 100 Nm³/h, and HyLYZER (PEM) with a capacity range from 70 to 3,000 Nm³/h. It has tested its electrolyzer series at small, medium, and large scale (PEM electrolyzer 20 MW) installed in 2021 in Air Liquide hydrogen production facility in Quebec.

SOLUTION HIGHLIGHTS

- Flexible operation with a H2 flow range of 1%-100%.
- 99.998% of Hydrogen purity
- Power to power, power to fuels
- 20 m^2 footprint
- Scalable up to 20 MW

At a glance

Type	Hydrogen generation
Year	1919
Key Feature	Flexible operation

HyLYZER 1000-30 Indoor system; modular, scalable, dual stack platform: 2 cell stacks of 500 Nm³/h (2,5 MW) to reach 1000 Nm³/h (5 MW), 30 barg (output pressure). Source: Cummins.

Linde - Develops technologies enabling H2 mobility

TECHNICAL DESCRIPTION

Linde's technology is designed for transport tanks (up to 5 tons of LH2) that maintain H2 cooled at -253 °C. H2 is transported by trucks to H2 fueling stations equipped with cryopump technology (cryogenic piston pump) that reduces energy consumption. H2 is fueled into the vehicles' target pressure.

SOLUTION HIGHLIGHTS

- Low energy consumption for compression and temperature management system
- High storage capacity onsite on a small footprint
- Little maintenance effort
- Compression is carried out by the cryo pump at 100 MPa, and a cryopump can deliver up to 100 kg/h

At a glance

Type	Hydrogen transportation
Year	1879
Key Feature	High storage capacity onsite

A highly compact and containerized design with adaptable technical specifications and scalability from small to large throughputs depending on hydrogen demand.

Hydrogenious - Enables safe and efficient storage and transport of hydrogen at ambient conditions

TECHNICAL DESCRIPTION

Green H2 is chemically bonded to a liquid carrier via hydrogenation (catalytic exothermic reaction: 9 kWh/kg H2 usable heat at > 200 °C), becoming an optimal energy storage medium. When needed for fueling, H2 is released through dehydrogenation (catalytic endothermic reaction: 12 kWh per kg H2 required at 300 °C).

At a glance

Type	Hydrogen storage
Year	2013
Key Feature	Can be transported in a conventional fuel infrastructure

SOLUTION HIGHLIGHTS

- 57 kg H2 uptake per cubic meter of liquid organic hydrogen carrier (LOHC)
- No molecular hydrogen is stored
- Storage without H2 losses can undergo for months
- Liquid state in a broad temperature range (-39 °C - 390 °C) and ambient pressure
- Transportable in conventional fuel infrastructure

Skid-mounted systems for large-scale H2 storage, designed for direct coupling with large-scale electrolysis. Plants can be custom-sized starting at 5.000 Nm³/h. Source: Hydrogenious.

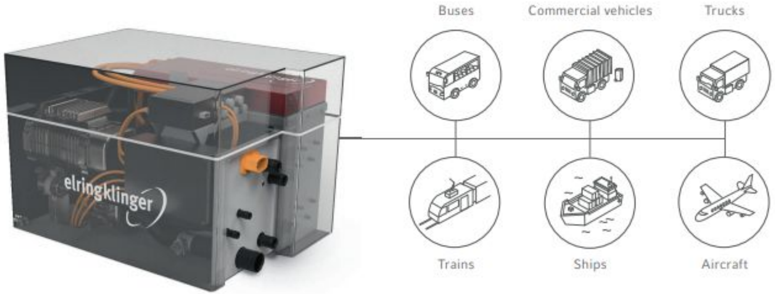
ElringKlinger - Produces proton exchange membrane fuel cells (PEMFC) for e-mobility

TECHNICAL DESCRIPTION

The PEMFC uses metal bipolar plates to achieve high power density, with a homogeneous distribution of voltage across the cell. The fuel cell stack consists of a pile of cells integrated into a plastic media module and contains sensors for pressure and temperature, valves, and condensate separators for the anode circuit.

SOLUTION HIGHLIGHTS

- Stacks are hybrid assemblies of metal components and high-performance plastics, which are mechanically stable and chemically resistant without adding weight
- > 12,000 hours of service life
- Capable of starting in freezing conditions
- Operates with H2 and air, and uses a glycol-based coolant for fuel cells



A low-temperature fuel cell that converts chemical energy to electrical energy using hydrogen and oxygen. Source: ElringKlinger.

At a glance

Type	Fuel cell
Year	1879
Key Feature	Operates with hydrogen and oxygen

Timeline for hydrogen-based energy adoption in commercial aviation

Short term (2020-2025)

- Replacement of on-airport ground support equipment currently running on liquid fuels and batteries with H2-powered fuel cell alternatives.
- Using H2 for treating crude or bio-crude oil to produce jet fuel with a lower carbon intensity.

Pushback tug

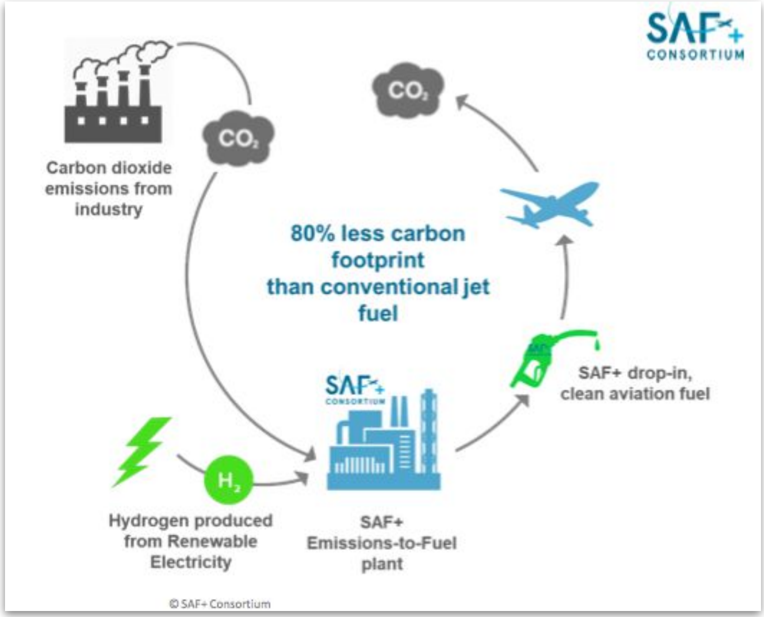
Container transporter

Aircraft catering vehicles

Examples of on-airport ground support equipment that will become powered by H2 fuel cells.

Medium term (2026-2035)

- On-aircraft applications that require no change to existing infrastructure. This concerns the production of synthetic jet fuel or "electrofuels."



SAF+, a consortium based in Montreal's east end, is planning to develop a drop-in, low-carbon sustainable aviation fuel (SAF) as an alternative to fossil jet fuel with over 80% lower lifecycle emissions. Image source: Skies Mag.

Long term (2036-2050)

- On-aircraft applications for H2 (and other H2 augmented fuels) that involve a redesign of existing airframes and supporting infrastructure.

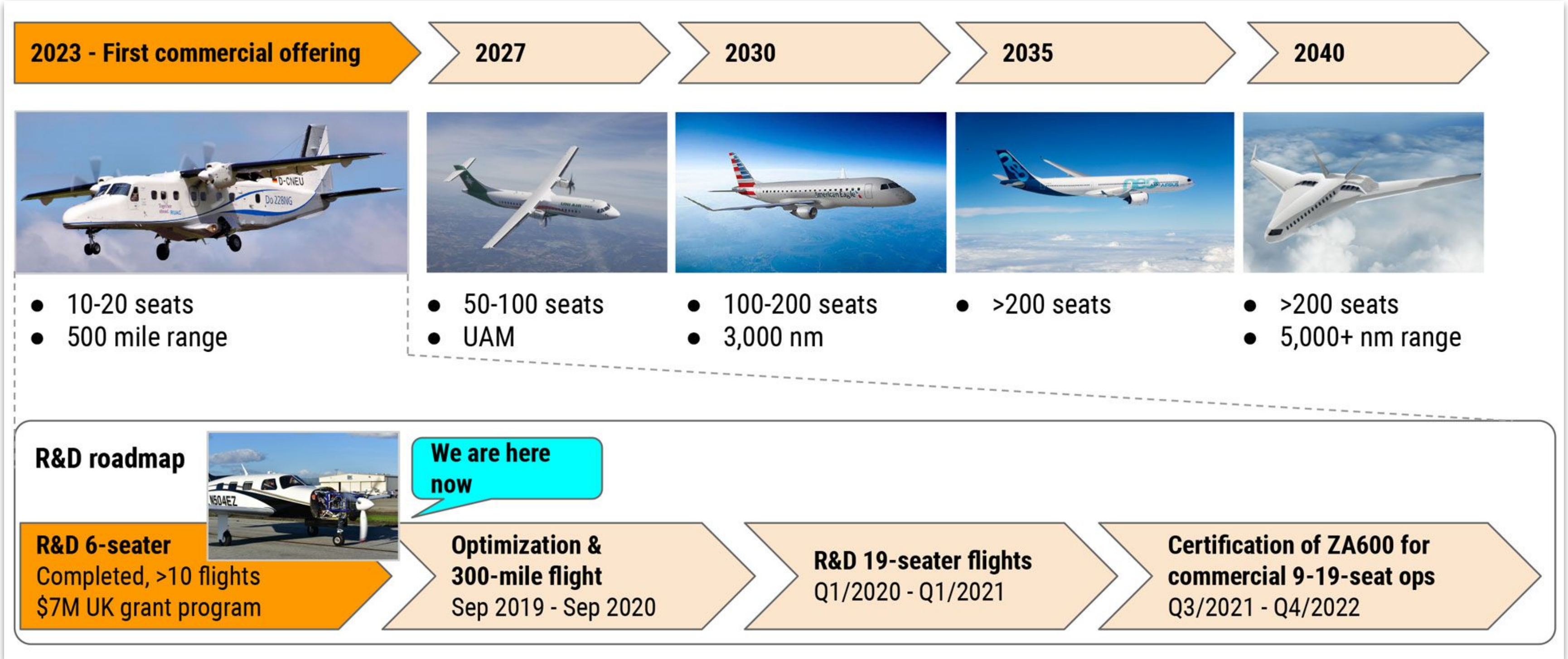
✗ Will not be compatible with conventional engines

✓ Requires novel engine architectures

✓ Requires novel electrical systems

An example of a redesigned aircraft to support a hydrogen-fuelled flight. Source: Boeing.

ZeroAvia by Ghenus Air’s timeline of hydrogen adoption into different types of commercial electric aircraft



Source: Ghenus Air

The 4 key innovation areas to focus on today and the projected timeline for reaching each milestone:

RESEARCH AREAS	EXAMPLES			Timeline
Components	Liquid hydrogen tanks	Fuel cells	Hydrogen turbines	2020 - 2035
Aircraft system	Commuter prototype	Short- to medium-range prototype	Long-range prototype	2020 - 2035; 2035 - 2050
Infrastructure	Efficient refueling and setup	At-scale liquefaction and liquid hydrogen handling	Liquid hydrogen hydrant refuelling	2020 - 2035; 2035 - 2050
Regulatory framework	Climate impact	Market activation mechanisms		2020-2028; 2020 - 2050

Developments in hydrogen-based energy from key players

Airbus ZEROe: Towards the world's first zero-emission commercial aircraft

ZEROe Airbus is leading a drastic change for decarbonizing commercial aviation. Airbus plans to bring to market the first ever zero-emission aircraft by 2035. An ambitious timeline is set to launch a ground demo in 2021 and flight demo by 2023.

The technology combines direct combustion of hydrogen through modified gas turbines with an embedded electric motor powered by fuel cells. Airbus has already started working on the details of the refueling of the aircraft as well as safe storage and distribution of hydrogen onboard the aircraft.

Two main structural challenges are related to design components:

1. Tank design and integration on the aircraft, without compromising performance and drag
2. Hydrogen cryogenics to keep the hydrogen liquid during all phases of flight

Overcoming these challenges will help to demonstrate the safety required to meet aeronautic regulations.

Turboprop

Turbofan

Blended-wing body

Source: Airbus

Boeing: Commercial jetliners, defense, space, and security systems

Since 2013, Boeing has taken the initial steps for using liquid hydrogen as a fuel to power unmanned aerial systems (UAS).

Phantom Eye is a high-altitude long-endurance (HALE) unit funded by the Missile Defense Agency with a $6.8 million contract. Phantom Eye was designed to offer persistent intelligence, surveillance, and reconnaissance and communications missions. The demonstrator aircraft was capable of maintaining its altitude for up to 4 days while carrying a 450-pound payload (e.g., multiple sensor packages for monitoring, tracking, and communications).

Phantom Eye achieves an altitude of 65,000 ft, with endurance of 4 days at 65,000 ft (19,800 m). Source: Boeing.

Most recently, the US Army has shown interest in developing a hydrogen-powered unmanned aerial vehicle. The US Army has provided a $7.2 million grant to researchers from Mississippi State University, Insitu Inc (a Boeing subsidiary), and Navmar Applied Sciences Corporation to demonstrate a liquid hydrogen–powered UAV and refueling system.

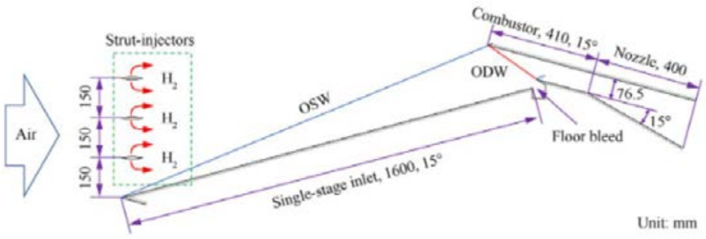
UAVs running on liquid hydrogen fly longer and farther, require less maintenance, and during flight, produce water vapor as the only emission.

Chinese Academy of Sciences: A hypersonic standing oblique detonation ramjet (SODRAMJET) engine

The Sodramjet, proposed by the Chinese Academy of Sciences, replaces diffusive combustion with an oblique detonation that is a unique pressure-gain phenomenon in nature. The Sodramjet engine model can reach Mach 16 level. A plane equipped with Sodramjet could arrive anywhere in the world in ~2 hours after departure.

Experimental data shows that the Sodramjet works steadily, and that an oblique detonation can be made stationary in the engine combustor and is controllable. Thus, it can be operated stably with high thermal efficiency at hypersonic flow conditions and potentially be powered by hydrogen.

The Sodramjet hypersonic airbreathing propulsion (HAP) is offering a new perspective to the future aerospace flight. HAP developments have been constrained due unsteady combustion leading to engine surging during operation, and thermal choking.



The prototype has 3 components: The engine (a single-stage air inlet), a hydrogen fuel injector, and a combustion chamber. Source: Jiang et al.

A wind tunnel simulating flight conditions at 9 times the speed of sound. The test verified performance in thrust, fuel efficiency, and operational stability. Source: Jiang et al.

Other recent developments

HyPoint Unveils Breakthrough Hydrogen Fuel Cell Prototype for Aviation and Urban Air Mobility

HyPoint unveiled the first operable prototype version of its turbo air-cooled hydrogen fuel cell system. Testing has shown that this system will be able to achieve up to 2,000 watts per kilogram of specific power. HyPoint will begin work with the US Department of Energy's National Renewable Energy Laboratory (NREL) to further test and validate its hydrogen fuel cell technology. HyPoint expects the system will be ready for testing at the beginning of 2022 and commercialized in 2023, at a price point of between $100-$500/kW (if mass-produced).

Plug Power and Universal Hydrogen Expand Partnership to Include Investment and Global Green Hydrogen Supply for Aviation

Plug Power Inc. announced an expansion of the relationship with Universal Hydrogen Co., a pioneer in hydrogen aviation. The companies previously announced a partnership to develop a fuel cell–based hydrogen powertrain for regional aircraft. The recent minority investment by Plug Power will enable Universal Hydrogen to complete the construction of a subscale aircraft powertrain by Q2 2021 and agreed to a global offtake relationship that will see green hydrogen become cost competitive with jet fuel by 2025.

Kuehne+Nagel to Supply 11 Million Liters of Sustainable Aviation Fuel to American Airlines

Kuehne+Nagel and American Airlines entered into an agreement to deploy more than 11M liters of SAF to enable a Boeing 787-9 Dreamliner passenger aircraft to fly 25 times carbon neutral around the world or transport 13 million kg of cargo from London to Dallas on a Boeing 777F cargo aircraft.

The result is a 75% reduction of additional carbon introduced into the global carbon cycle.

A comparison of competing technologies

	H_2 fuel cell	H_2 turbine	Synfuel
Climate impact	75-90% reduction	50-75% reduction	30-60% reduction[1]
Aircraft design	Only feasible for commuter to short-range segment	Feasible for all segments except for flights >10,000km	Only minor changes
Aircraft operations	1-2x longer refueling times for up to short-range	2-3x longer refueling times for medium- and long-range	Same turnaround times
Airport infrastructure	LH_2 distribution and storage required		Existing infrastructure can be used
Fuel supply chain	1.7x energy[2] required for fuel production		4.6x energy[3] required for fuel production
Cost comparison between H_2 and synfuel	Lower for commuter to short-range aircraft	Lower for medium-, higher for short-range aircraft	Higher than H_2 aircraft for commuter - medium-range

Major advantages

Major challenges

1. CO2 from direct air capture assumed
2. Assuming PEM electrolysis, compression, pipeline transport, liquefaction, storage, and distribution
3. Assuming PEM electrolysis, CO2 direct air capture, synthesis, pipeline transport, and distribution

Figure source: FCH

The potential roadblocks hindering widespread adoption of hydrogen in aviation

AIRCRAFT DESIGN

Hydrogen requires planes to be redesigned to incorporate large and heavy tanks to transport liquid H_2. For long-range aircraft, hydrogen tanks would increase airframe length and energy demand.

Weight-volumes are presently too high, which results in inadequate aircraft range compared to conventional fueled ones. Tanks to transport liquid H_2 need to be reduced by 50% compared to current prototypes.

The overall efficiency should target the design of lighter tanks (~12 kWh/kg/ gravimetric index of 35%) and fuel cell systems targeting 2 kW/kg, including cooling.

INFRASTRUCTURE

Refueling and on-ground handling of H_2 can be initially problematic due to the greater volume of liquid H_2 compared to current kerosene aircraft. The handling of H_2 will also require new safety regulations.

Another challenge is developing the large-scale transport, storage, and infrastructure solutions (e.g., trucks, mobile refueling platforms) required to supply airports with the necessary quantities of H_2 needed to fuel aircraft.

To be economically viable and scalable, hydrogen generation needs to happen onsite; and to achieve widespread adoption across the aviation industry, hydrogen must be made available at airports worldwide.

REGULATIONS

Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and ensure safety, have not been established. The handling of H_2 will also require new safety regulations.

Consumers need to have a positive perception in flying in a hydrogen-powered aircraft, which may be related to registering flawless operational and mechanical safety records.

OTHER TECHNICAL CHALLENGES

Current refueling times are too long; thus, to become a main source of power, refueling time needs to enable flow rates comparable to kerosene.

H2 turbines need to be optimized to also reduce nitrogen oxide emissions.

Durability of reliable components is still inadequate. Materials and components are needed to have extended lifetime (≥ 25,000 hours).

About the Authors

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Sofiane leads the high-tech, aerospace & defense, and automotive & logistics practices at PreScouter. For nearly a decade, he has worked with hundreds of F500 and G1000 clients across multiple industries, through which he has developed an expertise in key emerging technologies (such as 5G, IoT, AI/ML, blockchain, energy storage and generation, quantum sensing, and others) and a strong understanding of the associated business ecosystem and drivers pushing these sectors forward (e.g., key players and trends, roadblocks to commercialization, etc). Sofiane's strategic insights have ranged from technical due diligence for acquisition targets to identifying relevant markets for newly developed products based on emerging technologies and assessing market penetration strategies. Sofiane holds a PhD in Materials Science and Engineering from the Georgia Institute of Technology, where his research focused on nanotechnology and energy storage.

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